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This report summarizes the results of the research performed at Boston University (and in collaboration with researchers at the Air Force Research Laboratory Human Effectiveness Branch) on the acoustics and psychoacoustics of sound localization for sound sources near a listener's head, particularly in rooms where the effects of reverberation influence performance. The results of this work are unique in that little previous work has examined how the acoustics of the signals reaching a listener depend on the environment. Detailed analysis of the acoustic signals reaching a listener in a classroom demonstrates that the listener location relative to nearby walls has a dramatic impact on spatial acoustic cues. Source location relative to the listener also has a large impact; distortion of spatial cues generally grows with source distance and with source laterality. The ability to detect and understanding a sound source in the presence of a masker sound source improves when the competing sources are in different source locations. Results studying the effects of this "spatial unmasking" for nearby sources shows that the large interaural level differences that arise for nearby sources have an important influence on spatial unmasking. Furthermore, the influence of spatial unmasking decreases with growing levels of reverberant energy if the masker is a steady-state signal. However, the unmasking is robust in cases where the masking source is speech. The results suggest that even noisy, distorted spatial cues are sufficient to mediate competition between competing sources that are spectro-temporally complex, conditions in which "informational masking" dominates behavior.

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The Perceptual Impact of Simulating Sources within Reach of a Listener

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EXECUTIVE SUMMARY

This report summarizes the results of the research performed at Boston University (and in collaboration with researchers at the Air Force Research Laboratory Human Effectiveness Branch) on the acoustics and psychoacoustics of sound localization for sound sources near a listener's head, particularly in rooms where the effects of reverberation influence performance. The results of this work are unique in that little previous work has examined how the acoustics of the signals reaching a listener depend on the environment.

Detailed analysis of the acoustic signals reaching a listener in a classroom demonstrates that the listener location relative to nearby walls has a dramatic impact on spatial acoustic cues. Source location relative to the listener also has a large impact; distortion of spatial cues generally grows with source distance and with source laterality.

The ability to detect and understand a sound source in the presence of a masker sound source improves when the competing sources are in different source locations. Results studying the effects of this "spatial unmasking" for nearby sources shows that the large interaural level differences that arise for nearby sources have an important influence on spatial unmasking. Furthermore, the influence of spatial unmasking decreases with growing levels of reverberant energy if the masker is a steady-state signal. However, the unmasking is robust in cases where the masking source is speech. These results suggest that even noisy, distorted spatial cues are sufficient to mediate competition between competing sources that are spectro-temporally complex, conditions in which "informational masking" dominates behavior.

The distortion of spatial cues caused by reverberation degrades localization accuracy slightly. Furthermore, this distortion depends on where a listener is located in a room: specifically, how far he is from the nearest wall. However, listeners appear to learn how to overcome some of this distortion through experience in a room. A study of sensitivity to room acoustics suggests that listeners use spectral coloration to estimate their location in a room, and are relatively insensitive to other differences in the pattern of reverberation they hear.

Research to find efficient, robust, parametric models of room reverberation is underway. Such a model will provide a valuable tool to allow more detailed testing of the effects of room acoustics on auditory perception.

PERSONNEL

The personnel supported by and/or associated with this project were Barbara Shinn-Cunningham (principal investigator, Boston University), Nat Durlach (Boston University), Norbert Kopco (former graduate student and now part-time post-doctoral researcher), Boston University graduate students Antje Ihelefeld, Yusuke Naka, Matt Schoolmaster, Scarlet Constant, and Albert Ler; Massachusetts Institute of Technology graduate students Tara Brown, Sasha Devore, Kosuke Kawakyu, Neelima Yeddnapudi, and Davis Wamola; Boston University undergraduates Joan Brown, Lisa Mraz, Sona Patel, Suraj Ram, and Sanaz Sani Zhalehdoust, and undergraduate summer interns Alyssa Okun and Jenny Hamblett.

PUBLICATIONS

a. Journal Publications (7)

Shinn-Cunningham, BG, J Schickler, N Kopco, and RY Litovsky (2001). "Spatial unmasking of nearby speech sources in a simulated anechoic environment," J Acoust Soc Am, **110**(2), 1118-1129.

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DiZio, P, RM Held, JR Lackner, BG Shinn-Cunningham, and NI Durlach (2001). "Gravitoinertial force magnitude and direction influence head-centric auditory localization," J Neurophys, **85**, 2455-2460.

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b. Full Conference Papers (14)

Shinn-Cunningham, BG (2000). "Distance cues for virtual auditory space," in Proceedings of the IEEE 2000 International Symposium on Multimedia Information Processing, Sydney, Australia, 13-15 December 2000, 227-230 ***[peer-reviewed]***.

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Kopco, N and BG Shinn-Cunningham (2002). "Auditory localization in rooms: Acoustic analysis and behavior," in Proceedings of the 32nd International Acoustical Conference - EAA Symposium, Zvolen, Slovakia, 10-12 September 2002, 109-112.

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Shinn-Cunningham, BG (2003). "Spatial hearing advantages in everyday environments," in Proceedings of the ONR workshop on Attention, Perception, and Modeling for Complex Displays, Troy, New York, June 2003.

Shinn-Cunningham, BG and S Ram (2003). "Identifying where you are in room: Sensitivity to room acoustics," International Conference on Auditory Display, July 2003, 21-24 ***[peer-reviewed]***.

Devore, S and BG Shinn-Cunningham (2003). "Perceptual consequences of including reverberation in spatial auditory displays," International Conference on Auditory Display, July 2003, 75-78, ***[peer-reviewed]***.

Lane, CC, N Kopco, B Delgutte, BG Shinn-Cunningham, and HS Colburn (2003). "A cat's cocktail party: Psychophysical, neurophysiological, and computational studies of spatial release from masking," International Symposium on Hearing, Dourdan, France, August 2003, in press, ***[peer-reviewed]***.

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Shinn-Cunningham, BG (2004). "The perceptual consequences of creating a realistic, reverberant 3-D audio display," Proceedings of the International Congress on Acoustics, Kyoto, Japan, 4-9 April 2004 (in press).

Naka, Y, A Oberai, and BG Shinn-Cunningham (2004). "The finite element method with the Dirichlet-to-Neumann map for sound-hard rectangular rooms," Proceedings of the International Congress on Acoustics, Kyoto, Japan, 4-9 April 2004 (in press).

c. Book Chapters (3)

Shinn-Cunningham, BG (2001). "Creating three dimensions in virtual auditory displays," in Usability Evaluation and Interface Design: Cognitive Engineering, Intelligent Agents and Virtual Reality, MJ Smith, G Salvendy, D Harris, and RJ Koubek (eds.), (also in Proceedings of HCI International 2001, New Orleans, 5-10 August ***[invited talk; peer-reviewed conference proceedings]***), NJ: Erlbaum, 604-608.

Shilling, RD, and BG Shinn-Cunningham (2002). "Virtual auditory displays," in Handbook of Virtual Environments: Design, Implementation, and Applications, K Stanney (ed.), NJ: Erlbaum, 65-92.

Kopco N and B Shinn-Cunningham (2002). "Effects of cuing on perceived location of auditory sources," In: Intelligent Technologies: Theory and Applications, P Sincak, J Vascak, V Kvasnicka, and J Pospichal (eds), OS Press, 201-206.

d. Conference Abstracts (21)

5 presentations at mid-winter meetings of the Association for Research in Otolaryngology

9 presentations at meetings of the Acoustical Society of America (two of which were invited talks; one of which was the 2-hour-long tutorial lecture)

2 presentations at the National Academy of Sciences Frontiers of Science Symposium (one invited), an annual event for 100 outstanding young scientists from a range of disciplines

1 presentation at the International Conference on Cognitive and Neural Systems (invited)

1 presentation at the International Workshop on Binaural Hearing at Cocktail Parties held in the Hanse Wissenschaftskolleg in Delmenhorst Germany (invited)

1 presentation at the Workshop on Spatial and Binaural Hearing held in Utrecht, the Netherlands (invited)

1 presentation at the annual Harvard-MIT Health Science and Technology Forum

1 presentation at the annual Boston University Science and Technology Day

e. Invited Seminars (12)

Six invited seminars on work funded by the Air Force Office of Scientific Research were given by the PI during the last grant period at the University of Connecticut, the University of Sydney, Australia; the Technical University of Kosice, Slovakia; the Defense Science and Technology Organization, Melbourne, Australia; the Greater Boston Chapter of the Acoustical Society of America; Northeastern University (2), and Boston University (5).

RESULTS

1. Reverberant Head Related Transfer Functions in a Classroom

Head-related transfer functions were measured in a classroom for both a KEMAR manikin and human subjects for different source locations relative to the listener and listener locations in the room. Analysis showed that degradations in spatial cues depend on both the location of the source and the listener. For many of the source locations tested, the source was relatively close to (within a meter of) the listener. Even for these cases, the distortion of spatial cues by reverberation was marked.

Generally speaking, the distorting effects of reverberation increased as the ratio of the direct to reverberant energy decreased. Thus, spatial cue distortion increased with source distance. Reverberation also tended to fill in any notches in the total spectrum received at the ears of the listener because the direct sound intensity was low in these notches. This observation is of particular importance when considering how source location is resolved on the torus of confusion (Shinn-Cunningham et al., 2000), which depends on the computation of spectral shape and has been associated with the location of notches in the received spectrum (Jin and Carlile, 1999; Jin et al., 1999; Macpherson and Middlebrooks, 2002). However, in a room, these notches appear to be the least robust spectral feature in the total signal reaching the listener.

For nearby sources, the direct sound energy levels reaching the two ears differed because of the large ILDs that arise for a nearby, lateral source. In this case, the distortion caused by reverberation was more pronounced in the far ear, which received less direct sound energy. As a result, spectral features were much less distorted in the near ear than the far ear; in other words, the near ear conveys more useful information about vertical angle than does the far ear (e.g., see Morimoto, 2001). However, the distortion of interaural level and time differences depended on the distortion in the ear with the less advantageous direct-to-reverberant energy ratio. As a result, we found that distortion of interaural time and level increased with source laterality, particularly for nearby sources.

When a listener is relatively far from any reflecting surface, the effect of the reverberation was to randomly distort the spectral and interaural cues important for sound localization; thus, by averaging over time or over frequency, the listener might able to overcome these acoustic distortions. In contrast, when a listener was near to a large reflective surface like a wall, the early, intense reflections from the wall cause comb-filtering effects, leading to systematic variations in the received spectrum and interaural differences. These systematic distortions resulted in more challenging listening conditions in which listeners make larger errors in localization (e.g., see Shinn-Cunningham, 2001).

Shinn-Cunningham, 2000) presents a summary of the acoustic cues that vary with source distance in a room, such as overall level, direct sound level, direct-to-reverberant energy ratio, and other features, based on our classroom measurements. Analysis shows that the direct-to-reverberant energy ratio varies reliably with source distance even for nearby sources. Acoustic analysis of room HRTFs is is described more fully in the M.Eng. Thesis of Tara Brown Brown, 2000 and in our recent JASA submission (Shinn-Cunningham et al., under revision).

3. Spatial Unmasking: Detection

Kopco and Shinn-Cunningham, 2003) presents results of experiments and analyses investigating how simple detection thresholds for tones in noise vary with the directions and distances of the target and a broadband masker source. Acoustic analysis showed how much of the dependence on spatial configuration was the result of simple energy effects versus how much came about through binaural interactions. Predictions of existing binaural models accounted for the basic pattern of results, but could not account for inter-subject differences. We are currently extending these experiments to investigate tone detection thresholds in the presence of room reverberation.

Lane et al., 2004) is the result of a collaborative effort with researchers at MIT and the Massachusetts Eye and Ear Infirmary. This study directly compared psychophysical results and computational model predictions with physiological measures of spatial unmasking for broadband targets. Results of our psychoacoustic and modeling efforts showed that if there is a single frequency band in which performance is predicted to be much better than in other bands, performance could be accounted for by the "best band" prediction alone. However, if many different frequency bands yielded similar threshold predictions, performance was better than can be predicted from any single band, suggesting the importance of across-frequency integration in spatial unmasking of broadband targets.

4. Spatial Unmasking: Intelligibility

Shinn-Cunningham et al., 2002) shows that for sources very near the head, masked speech intelligibility may not always be well predicted by existing models of binaural speech unmasking. In particular, for some signal and masker configurations speech intelligibility was slightly (but significantly) worse than predicted by analysis taking into account both the signal-to-noise ratios at the two ears and the interaural differences resulting from signal and noise. Many of the observed model failures occured in cases where interaural level differences were large because at least one of the sources (signal or masker) was near the head, cases which have not been extensively tested in previous studies.

Shinn-Cunningham, 2002) summarizes preliminary analyses of experiments investigating the effect of reverberation on speech unmasking and intelligibility. These results suggest that for moderate-sized rooms, speech intelligibility and spatial unmasking of speech is only minimally affected by reverberation, at least if the masking source is relatively close to the listener. This result is encouraging, since it suggests that moderate levels of reverberation can be used in headphone simulations to provide accurate distance percepts without dramatic effects on speech intelligibility or spatial unmasking. In addition to conducting more extensive analyses of these results, we are currently running a closely-related study in which the speech materials are spoken in a conversational manner, rather than carefully enunciated (e.g., see Payton et al., 1994).

Devore and Shinn-Cunningham, 2003) describes experiments investigating the ability of subjects to identify obstruent consonants in reverberant and noisy environments. These experiments focused on the obstruent consonants because they contain very rapid temporal fluctuations that we hypothesized would be disrupted by reverberation. The acoustic features enabling discrimination of these consonants, however, occur at relatively high frequencies, above the range in which most "binaural unmasking" is thought to arise. Thus, we hypothesized that binaural performance would not be significantly better than monaural performance using the ear with the better signal-to-noise ratio. Interestingly, we found that for these stimuli, binaural listening improves performance not only when the target and masker were in different locations (as one might expect based on previous studies of spatial unmasking, at least when the target has low-frequency content) but also, surprisingly, when target and masker were in the same location. These results suggest that the benefits of binaural presentation go beyond the low-frequency binaural benefit addressed by most studies of spatial unmasking.

We recently performed a pilot experiment in conjunction with Doug Brungart of AFRL/HECB examining spatial unmasking when target and masker sources are simulated at different distances in the

median plane using reverberant HRTFs (at distances of 15, 40, and 100 cm). In this study, both target and masker sources were taken from the same speech corpus Brungart, 2001 and were sufficiently similar that the task emphasized informational masking. After processing through reverberant HRTFs, the stimuli were normalized to have the same RMS level, thus taking out natural variations in intensity with distance.

A summary of some preliminary results is shown in Figure 1 for binaural (left column) and monaural (right column) presentation. Overall, binaural performance is better than monaural performance (compare percent correct scores in left and right columns). For monaural presentations (right column), performance decreased with increasing target distance (performance decreases when moving from top panel to bottom panel) and with increasing masker distance (within each panel, performance is either constant or gets worse as masker distance increases). This finding suggests that monaural performance decreases with increasing

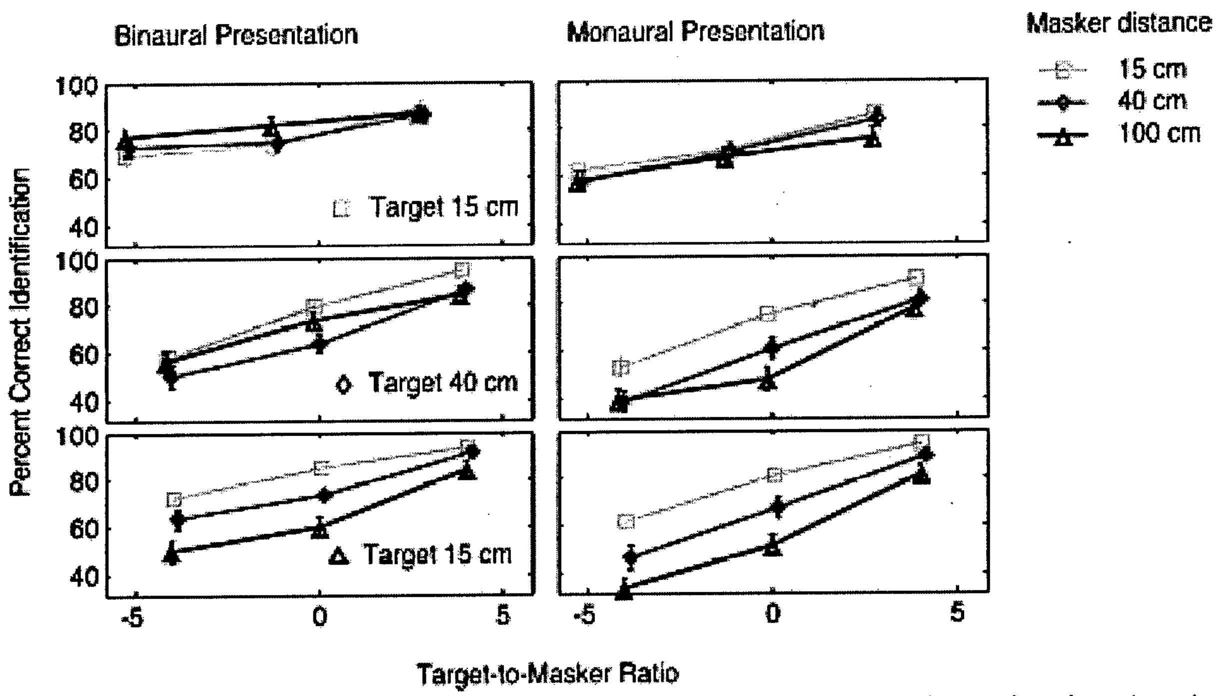

Figure 1: Correct percent identification as a function of target to masker ratio when target and masker are both taken from the CRM corpus (e.g., see Brungart, 2001). Each panel shows results for one target location in the median plane, with the masker location varying in distance in the median plane. Left column shows results for binaural presentation; right column for monaural presentation.

reverberation in either target or masker, as the direct-to-reverberant energy ratio decreases with increasing source distance. Binaurally, the results were strikingly different. Indeed, in the binaural conditions, performance appeared to depend on the *difference* between target and masker distances, with performance best when this difference was largest and worst when this difference was smallest (consider the results in left column of Figure 1). Given that reverberation provides a cue for source distance, these results are consistent with the idea that interference between the qualitatively similar target and masker decreases with differences in perceived source distance.

5. Informational Masking

Durlach et al., 2003a; Durlach et al., 2003b) are concerned with informational masking. The former paper presents some of the issues that must be considered in informational masking studies. The latter

paper presents results of experiments showing that informational masking decreases when target and masker are made dissimilar (either through their spatial position, their temporal envelopes, or in other dimensions). These results also demonstrate that the susceptibility of a particular subject to informational masking on one kind of task partially predicts their susceptibility to informational masking on other tasks.

6. Sound Localization

Kopco and Shinn-Cunningham, 2002a) summarizes a study in which listeners were asked to localize sound in a room when seated at different locations in the room. Results showed that localization judgments improved with experience in a room and that some room locations lead to better localization performance than others. Acoustic analysis showed that the effects of the reverberation on acoustic cues in "difficult" room locations were more pronounced than in "easy" room locations, correlated with behavior. Further, results showed that learning in one room location at least partially generalizes to other room locations, suggesting that the characteristics of a room that are learned are not specific to details in the reverberation pattern but are consistent for different listener locations within the same room.

Kopco and Shinn-Cunningham, 2002b) reviews how a preceding stimulus biases localization of a subsequent sound in a room. Acoustic analysis showed that the observed result was not the result of purely acoustic factors; instead, results suggest that involuntary interactions occurred that caused systematic distortions of spatial auditory perception. A follow up study suggested that these effects depend on the reverberation present in a room.

We also have examined distance perception for sources simulated for different listening environments. We hypothesized that listeners must calibrate their distance judgments to the particular environment in which they are located. To test this, we asked listeners to estimate distance either in conditions when anechoic trials were intermingled with trials simulating different listener locations in a classroom or when the listening environment was kept constant for all trials in a block. Results were unequivocal: subjects were much more consistent in their judgments of distance when the room environment was held fixed throughout a block. We are currently conducting a follow-up study to determine if less extreme differences in room conditions produce the same levels of confusion (i.e., intermingling trials simulating a large classroom with trials simulating a very small room) in order to determine how finely listeners calibrate their distance judgments to the acoustical environment.

7. Sensitivity to Reverberation Patterns

Shinn-Cunningham and Ram, 2003) describes results of an experiment investigating how sensitive listeners are to *where* they are located in a room, based solely on the HRTF-simulated signals presented over headphones. Four listener locations (all for the same room) were tested, differing in the number of walls near the listener and the listener's orientation relative to these walls (listeners were either in the room center, with their back to a wall, with their side to a wall, or in the corner of the room). Results showed that listeners performed relatively poorly on this task, and that they performed better with monaural presentations using the ear farther from the source than with binaural presentations or monaural presentations with the ear nearer to the sound source.

Subsequent analysis of acoustic cues that might explain the pattern of results identified the shadowed-ear spectral shape as the most likely cue; spectral shape cues accounted for the relatively poor performance using the near ear compared to the far ear and for different patterns of confusions (predicting which room locations listeners would be most likely to confuse). We hypothesize that when presented with reverberant binaural stimuli, the auditory system computes a central spectrum that averages the left and right ear spectra in order to reduce the spectral distortion of echoes. This reduces the salience of the far ear spectral shape cue, which shows greater variation with listener location than does the near ear spectrum. This form of processing will generally reduce spectral distortion caused by reverberation because the distortion differs in the left and right ears. However, this result is consistent with the observation that listeners are less accurate in judging the pattern of reverberation present in binaural stimuli compared to monaural stimuli.

8. Neural Modeling

Shinn-Cunningham and Kawakyu, 2003) shows results of our modeling of the response of a population of medial superior olive (MSO) neurons in response to sources from different locations relative to the listener in different acoustic environments. The MSO is the brainstem site in which ITD cues are extracted using a binaural coincidence mechanism. The paper discusses how reverberation distorts the ITD cues extracted in the brainstem by causing time-varying noise compared to the values that would be extracted in an anechoic setting. The main conclusion of the paper are that any instantaneous estimate of source direction in any particular frequency channel in the model is very unreliable in a room. However, integration over frequency and / or time will produce reasonable estimates of source direction.

We also found that the MSO output is only noisy and unreliable when one considers what happens in a room with reverberation. In anechoic space, the only source of ambiguity in the computation of ITD arises from internal noise that is orders of magnitude smaller than the external noise caused by reverberation. However, in a room, decorrelation from echoes and reverberation radically distorts the computation of interaural time differences.

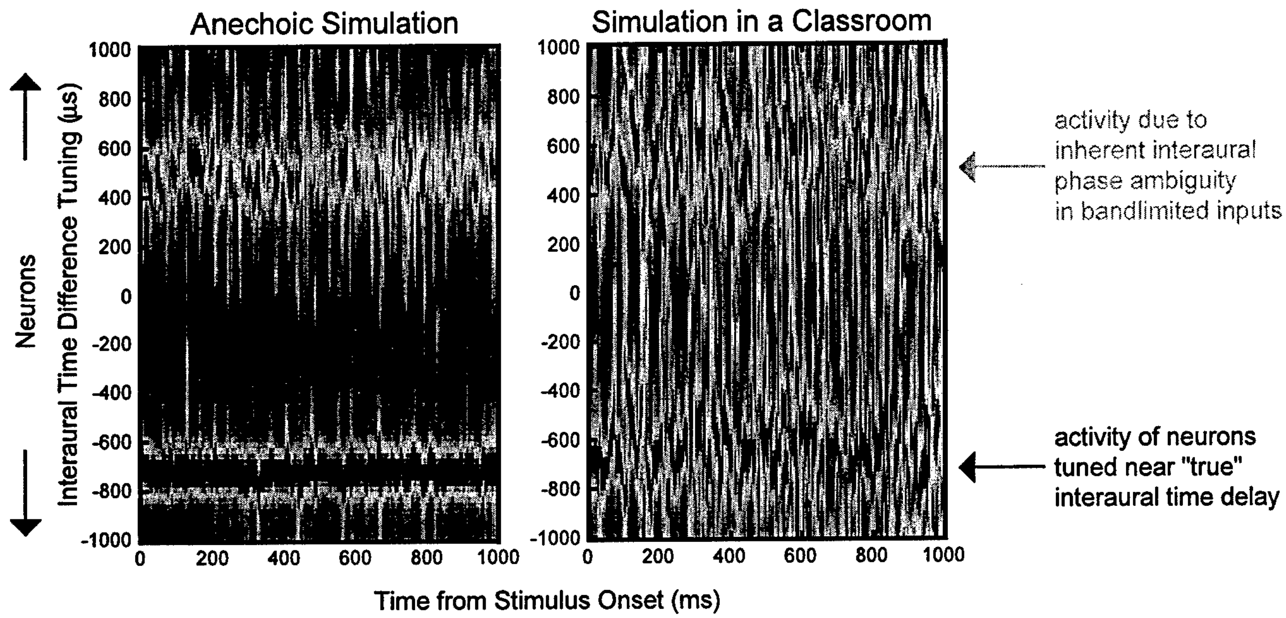

Figure 2. Model of a population of brainstem (MSO) neurons tuned to 825 in response to a source presented in anechoic space (left) or with the listener in the center of a classroom (source simulated at azimuth 90° to the left of the listener at a distance of 1 m). Note that the secondary peak due to phase ambiguity is much more prominent in the presence of reverberation.

Figure 2 shows the output of a population of medial superior olive or MSO neurons with the same center frequency (825 Hz), each of which is "tuned" to a different interaural time delay. The activity of each individual neuron is plotted as a horizontal stripe of activity, with the horizontal axis representing time. The left panel shows the model neural population activity when a source is presented from the left side of a subject in anechoic space (leading to a well-defined, constant peak activity in the output of the MSO neurons "tuned" to interaural time delays around –700 µs, as well as a second smaller and less consistent burst of activity from neurons "tuned" exactly one cycle away, at –700 µs + 1/825 s). The right panel shows the population output for the same sound source presented in a small classroom (leading to randomly-varying activity, even though the peak activity is, on average, at the "correct" position). In

addition, the primary and secondary activity peaks are roughly comparable in amplitude and temporal variability in the presence of interaural decorrelation from room reverberation.

These results demonstrate how listening in a room could disrupt directional hearing. The observed variations in ITD cues as a function of time suggest that one strategy for improving localization performance in a room would be to increase the time over which spatial cues are integrated to estimate source location. Such simple adjustments of spatial computation could explain why experience from one location in a room at least partially generalizes to other listener locations in the same room: the optimal time over which to integrate spatial cues is likely to be very similar for different listener positions. This sort of physiologically-inspired modeling demonstrates the importance of the variability caused by reverberation over time and frequency and how this variability depends on the acoustic environment.

9. Room Modeling

We have found that simple room-image models (such as Allen and Berkley, 1979) are unable to account for changes in reverberant energy reaching the ears with changes in source location when the source is very near the head. Analysis shows that gross errors in the reverberation level predicted using "standard" image method arise from interactions of the head with the reverberant field (i.e., the pattern of reverberation is substantially changed by the absorption and reflection of sound by the head and body). Thus, for nearby sources, more complex simulation approaches are necessary to get even the gross characteristics of reverberation "correct." These findings are discussed further in Shinn-Cunningham et al., 2001).

Yusuke Naka, a graduate student from the Department of Aerospace and Mechanical Engineering, is working on a room acoustics model based on finite-element methods as part of his dissertation research (see Naka et al., 2004 for a description of his initial efforts). This effort makes fewer assumptions than our previous efforts, which ignored the effects of the listener on the pattern of reverberant energy radiating through the room.

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